

Landsat/AVHRR/Hydrography Integration, Penobscot Bay Project

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July 1999

Hydrographic data taken during the 1997 field season by Pettigrew et al. are examined and compared with results from the analysis of Landsat TM and AVHRR data undertaken by Byrne and Thomas, 1998. Although the hydrography is complex, distinct water masses can be identified and in some cases traced through the year, enhancing our understanding of the circulation patterns and of their relationship to the patterns seen in the remote sensing imagery.

MARCH:

The March, 1997 cruise consists of 30 hydrographic stations in Penobscot Bay. The geographic distribution of the stations is pictured in Fig. 1a. The data reveal a 3-layer structure with distinct surface, intermediate, and bottom water layers. Bottom temperatures in this season range from 1.7C in the extremely well-mixed eastern bay up to 2.4C in the much more stratified western part of the bay. In the northwestern bay, north and west of Islesboro island, surface waters (0-10m) are the coldest and freshest, with salinities below 29.00 psu and temperatures around 1.5C. The area covered by this surface water (Fig. 1, in purple) corresponds with the regions influenced by the river in the spring Landsat imagery. Bottom waters in this region are also the freshest, with salinities consistently less than 31.52psu. For the most part, the T-S relationship in the northwestern bay is tight, meaning that a measurement of surface salinity will be a reasonable indicator of intermediate ($24.5 < \sigma\text{-theta} < 25.0$) or bottom ($\sigma\text{-theta} > 25.0$) temperature and salinity. Surface temperature, however, is not a good indicator because of the existence of another similar water column in the central part of Penobscot Bay. In the central bay, temperatures are similar (1.0-2.4C, compared with 1.4-2.4C in the northwestern bay) but about 0.1-0.2psu saltier along a given isotherm (Figs 1a,b, purple and yellow). A few 'transitional' stations show bottom T-S values typical of the central bay, but surface waters more akin to those in the northwestern bay (e.g., station 33, plotted in black in Fig. 1).

The southwestern part of Penobscot bay (Fig. 1, plotted in magenta and cyan) is warmer and saltier overall than the northwestern part of the bay. It is still quite stratified compared with the eastern bay (Fig. 1, plotted in blue). Most of the stations follow a single T-S curve, but at the north end of this region the upper waters are replaced by the cooler, fresher northwestern water. At the northern end of the central bay, a similar saline-deep to fresh-surface transition is seen (Fig. 1, in red), with bottom water salinities higher than anywhere else in the central bay. This indicates an external source of deep water for the central bay.

The southeastern part of Penobscot bay is characterized in the March data by being the most well-mixed part of the bay, with salinities from ~30.88 to ~31.35. Although the mean salinity is highest in the east, it should be noted that in this season, the most saline water in this cruise was found in the bottom water to the southwest. However, the far southeast of the bay, the location of the most saline water at other times of the year, was not sampled during this cruise. In general, in this

season, the surface temperatures are colder than the intermediate bottom waters as would have been the case for the preceding winter.

APRIL:

The April cruise consists of 54 hydrographic stations taken inside and just offshore of Penobscot Bay. By April the thermal stratification seen in March has reversed; the surface waters of Penobscot Bay ($\sigma\text{-}\theta < 24$) are warmer than the intermediate and bottom waters (Fig. 2). The majority of bottom and intermediate waters in April fall into approximately the same salinity range as in March, or 30.0-31.8, but the northwestern bay is flooded with fresh water at the surface, with salinities below 19.0, meaning that the bay is far more stratified than it was the month before. Temperatures almost everywhere have risen 2-5C, with the largest gain in the upper part of the water column.

The relatively cold, fresh waters found at the bottom of the northwestern bay in March have warmed only ~1C and become about 0.2psu saltier and appear to be spreading out from this region as an intermediate water layer. This intermediate water mass, dubbed "Penobscot Bay Intermediate Water" (PBIW) by Byrne and Pettigrew, has a core T-S of 3.2C and 31.5psu in the April data. The presence or absence of this water is not able to be deduced from surface quantities alone and its existence adds a degree of complexity to the hydrography of Penobscot Bay.

The southwestern part of Penobscot Bay is in the April data relatively warmer and saltier than the northwest, with up to 10psu difference along an isotherm. This extremely strong contrast, two orders of magnitude larger than the contrast in March, is presumably due to the outflow of the Penobscot river, the climatological maximum of which (April 20) falls only 6 days before these data were collected. Only those stations south of Deer Isle, an area not occupied during the March cruise, remain relatively unaffected by the fresh influx at the surface. In these data, the saltiest water is in the southeast, reaching salinities > 32 .

JULY:

The July cruise consists of 58 stations taken in and immediately to the south of Penobscot Bay. By July, surface salinities have increased slightly but are still significantly fresher (up to 4.5psu) than in March. Temperatures in all parts of Penobscot Bay have risen substantially above the March and April values, with bottom temperatures about 5C warmer and surface temperatures up to 18.5C higher than in March. Bottom salinities at similar locations have increased by approximately 0.2 psu from their March values.

By July, the difference between the (north)western and (south)eastern parts of Penobscot Bay is well-developed, as it is in the summer Landsat imagery. A sea surface temperature front, present in much of the summer imagery, appears to separate the two regimes. Sea surface temperatures north of the front are generally $> 16\text{C}$, while south of the front they are generally around 14C. The two regimes extend through the intermediate and into the bottom waters of Penobscot Bay;

intermediate and bottom waters in the northwestern half of the bay are cooler and fresher than in the southeast, with the difference in bottom water salinity hovering around ~ 0.5 psu.

In July as in the two earlier cruises, the southeastern part of Penobscot Bay is the most saline, with salinities up to 32, and the most homogeneous. Outside of the bay salinities are higher yet (Fig. 3, cyan, magenta and blue), with bottom salinities > 32 , and relatively weak stratification.

Penobscot Bay Intermediate Water is a prominent feature in the far northwestern stations west of Isleboro (Fig. 3, in purple), with a core T-S of 8.3C and 31.0 (Figs. 3, 4); remnants of this water can be seen in the central channel (Fig. 3, in red) and even as far east as 68 degrees 49.85'W. The PBIW could be spreading out from a northwestern source region, or it could have been formed locally in several places in the bay. The former hypothesis is considered the stronger one, as in several of the northwestern stations occupied during this cruise, PBIW was found in a thick isopycnal layer extending to the bottom of the water column (Fig. 4). It is not known whether the persistence of PBIW is an annual event or whether it only occurs in some years. The strength, presence or absence of the PBIW layer is not indicated by the location of the sea surface temperature front or by the surface salinity. Because of this complexity, surface properties cannot be taken as reliable measures of subsurface structure or circulation patterns in Penobscot Bay, which show at least 3 layers of structure and several modes of variability.

ACKNOWLEDGEMENTS <these are for the entire report, not just the Appendix>

This work was supported by a grant from the National Environmental and Satellite Data and Information Service (NESDIS) division of the National Oceanic and Atmospheric Administration (NOAA). We would like to thank Neal Pettigrew for allowing us the use of his hydrographic data, and Peter Cornillon for having provided the high-resolution, Pathfinder-processed AVHRR data.